Precision Clocks Using Superconducting Niobium Cavities*

by
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INTRODUCTION

- Applications of high-Q cavities: precise time-keeping, planetary navigation, precise measurements of physical constants.

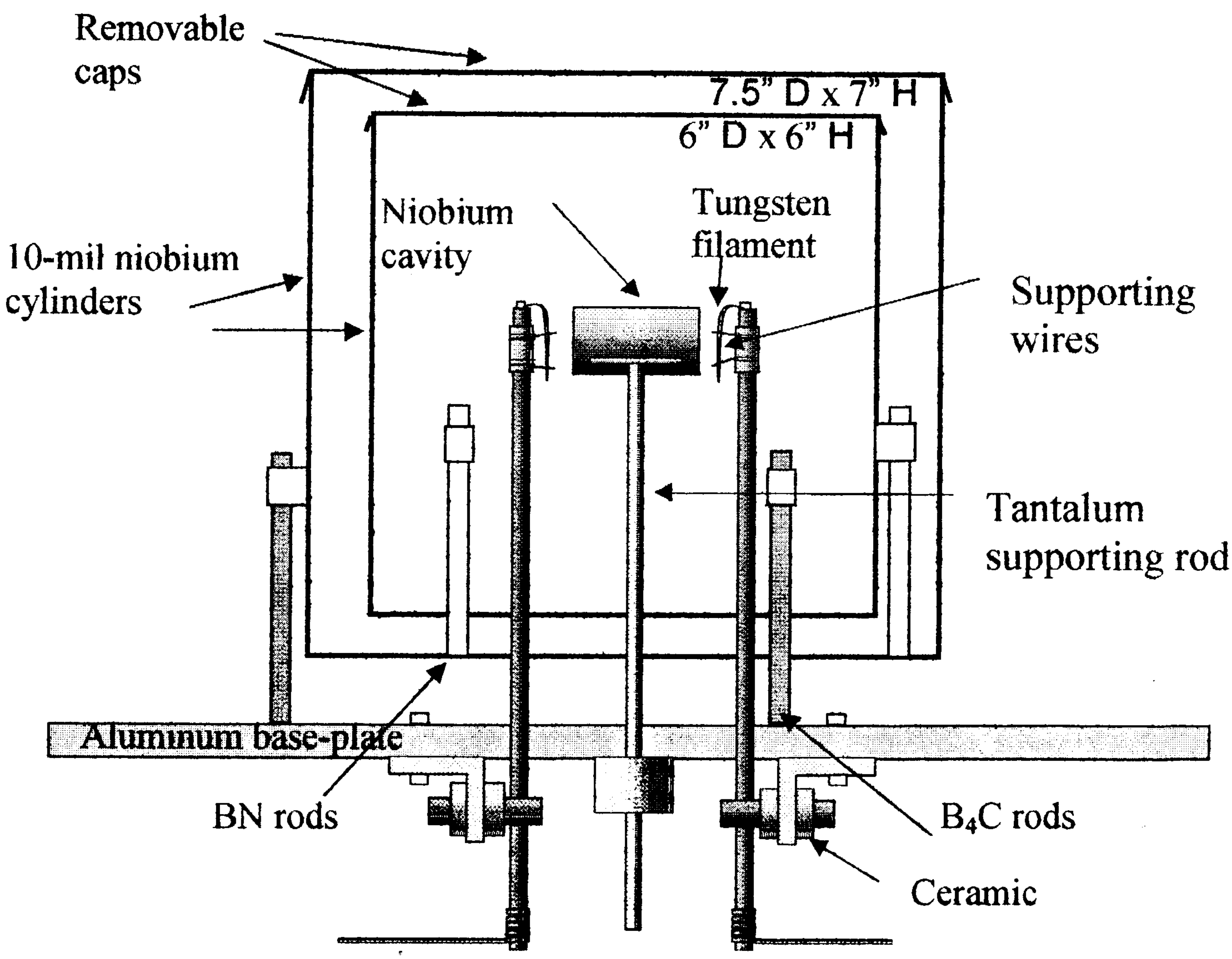
- Low temperature superconductor cavity offers a feasible solution because of its extremely high quality factors (Q's).

- The record Q is of the order of 10^{11} (Turneaure and Viet, 1970).

- Goal: Utilizing modern electronics, we will build a clock with stability on the order of 10^{-17} using cavities with Q of the order of 10^{10}.

Ultra-high Vacuum Annealing

- E-beam heating cavity up to 1900 °C for 12 hours or more in pressure as low as 1×10^{-9} Torr.
- Besides reducing irregularities on cavity surfaces and in the lattice, vacuum annealing will also help drive out H_2 and O_2 from within the niobium lattice.



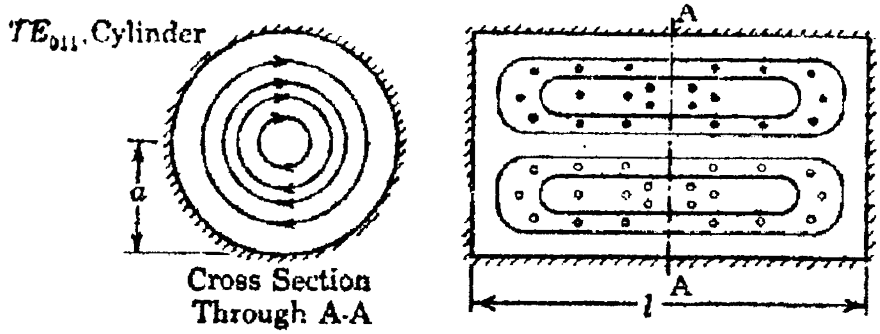
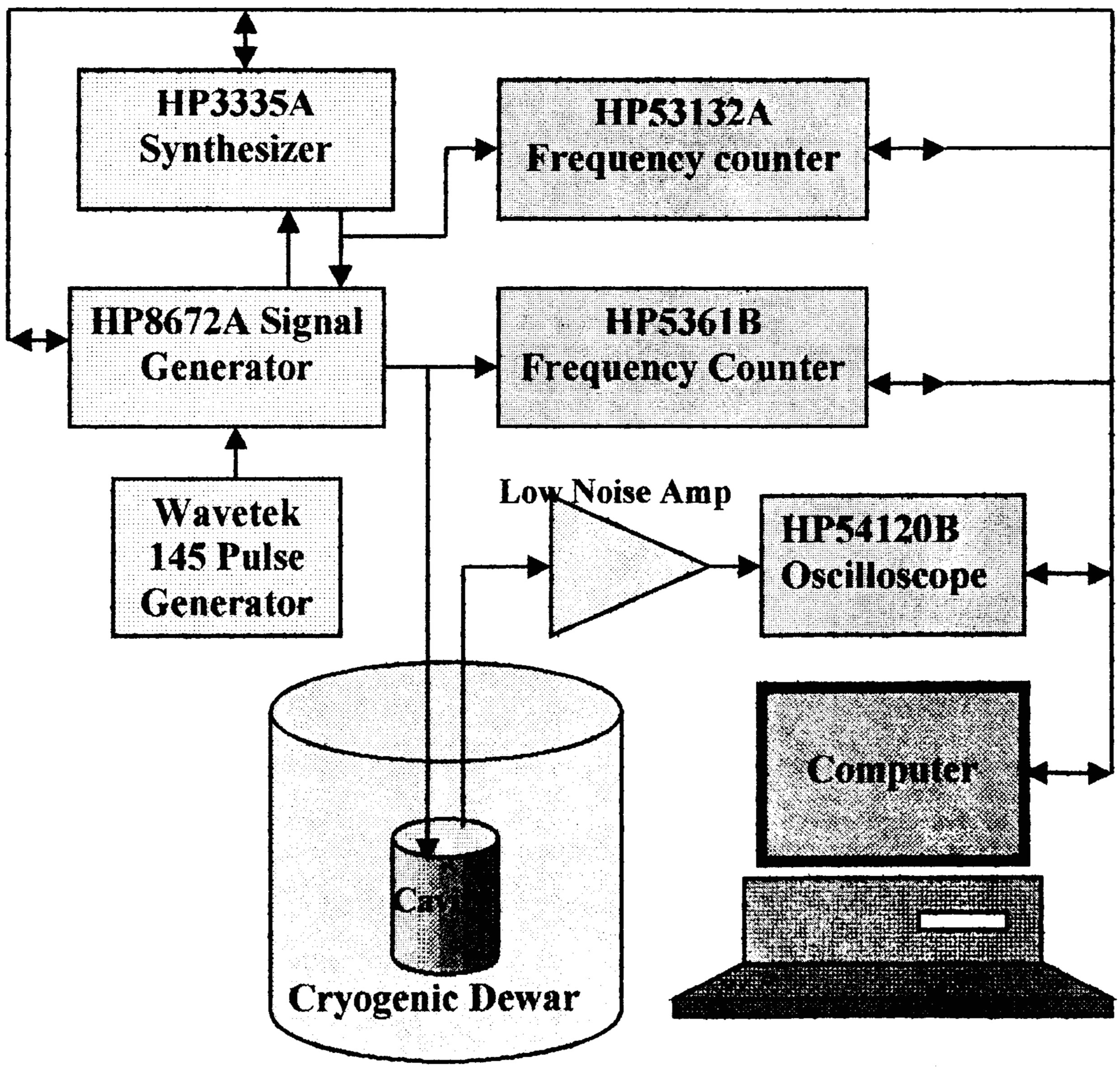


Figure 2.1. Field patterns for TE_{011} mode.

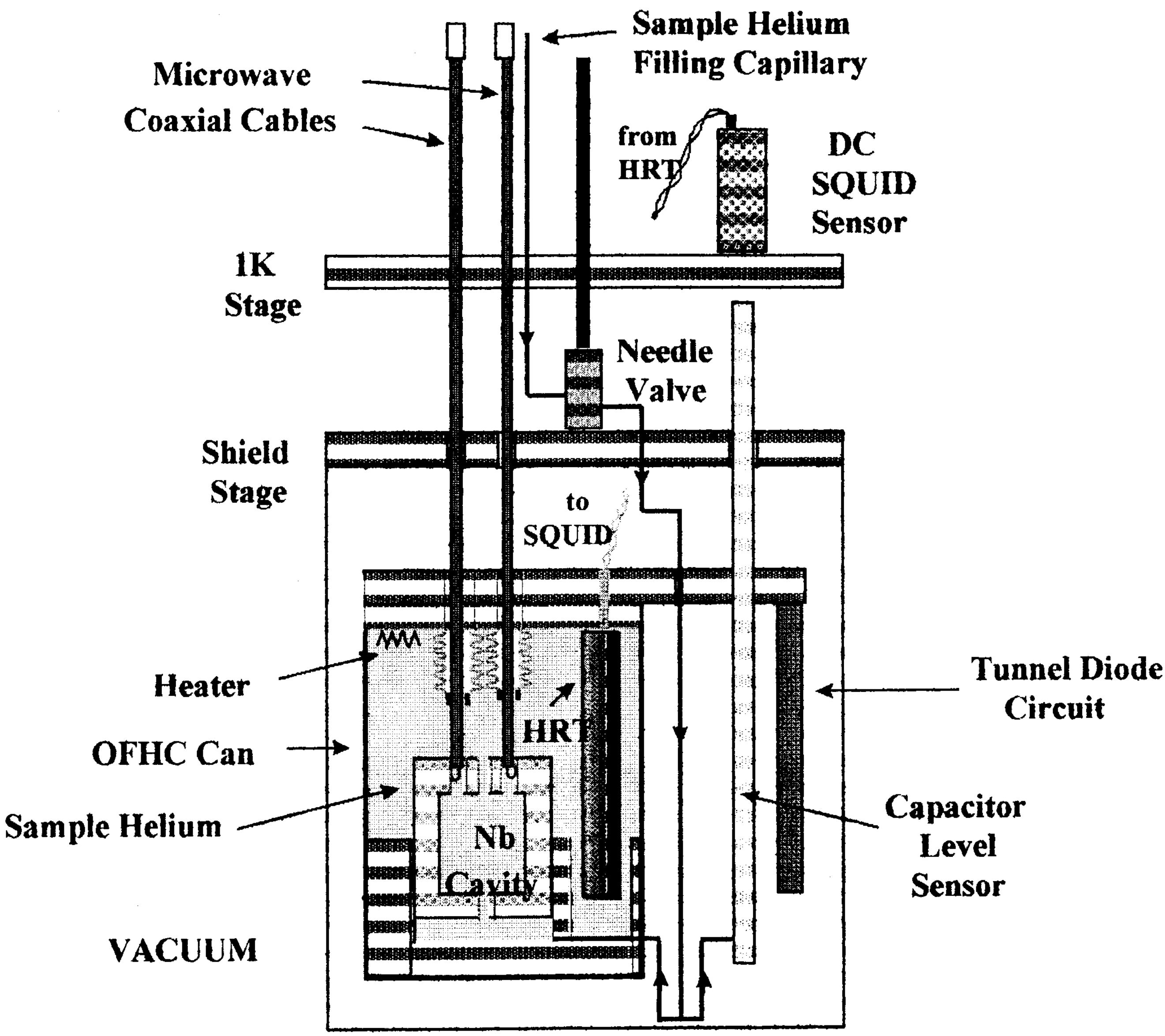
Quality Factor Characterization

- Use the Microwave Characterization System to find the resonant frequency and measure the Q-value of an annealed cavity.

- The system has resolution of 1 mHz and is capable of measuring Q-values on the order of 10^{10}-10^{12}.



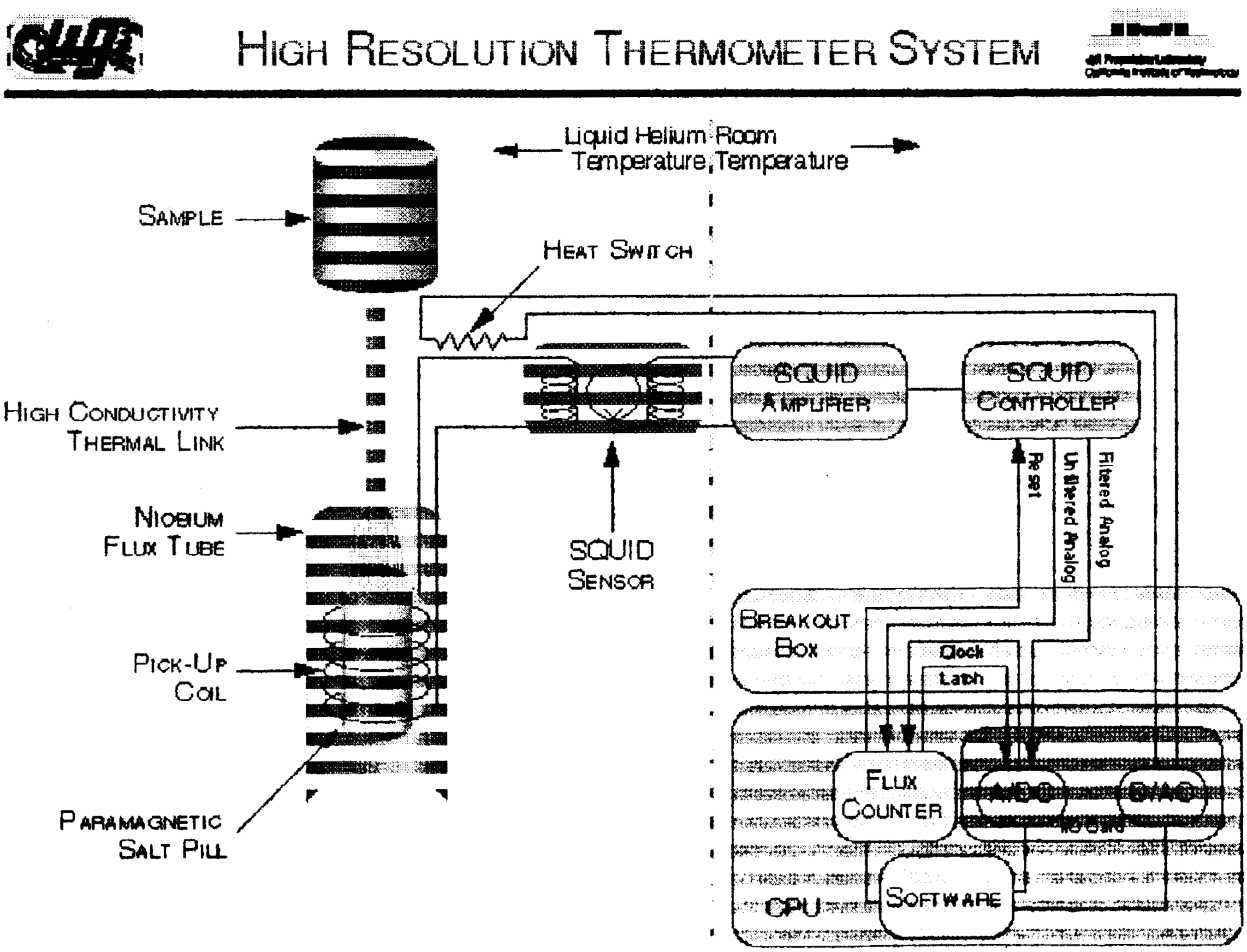
Refrigeration and Cavity Mounting



Temperature Control

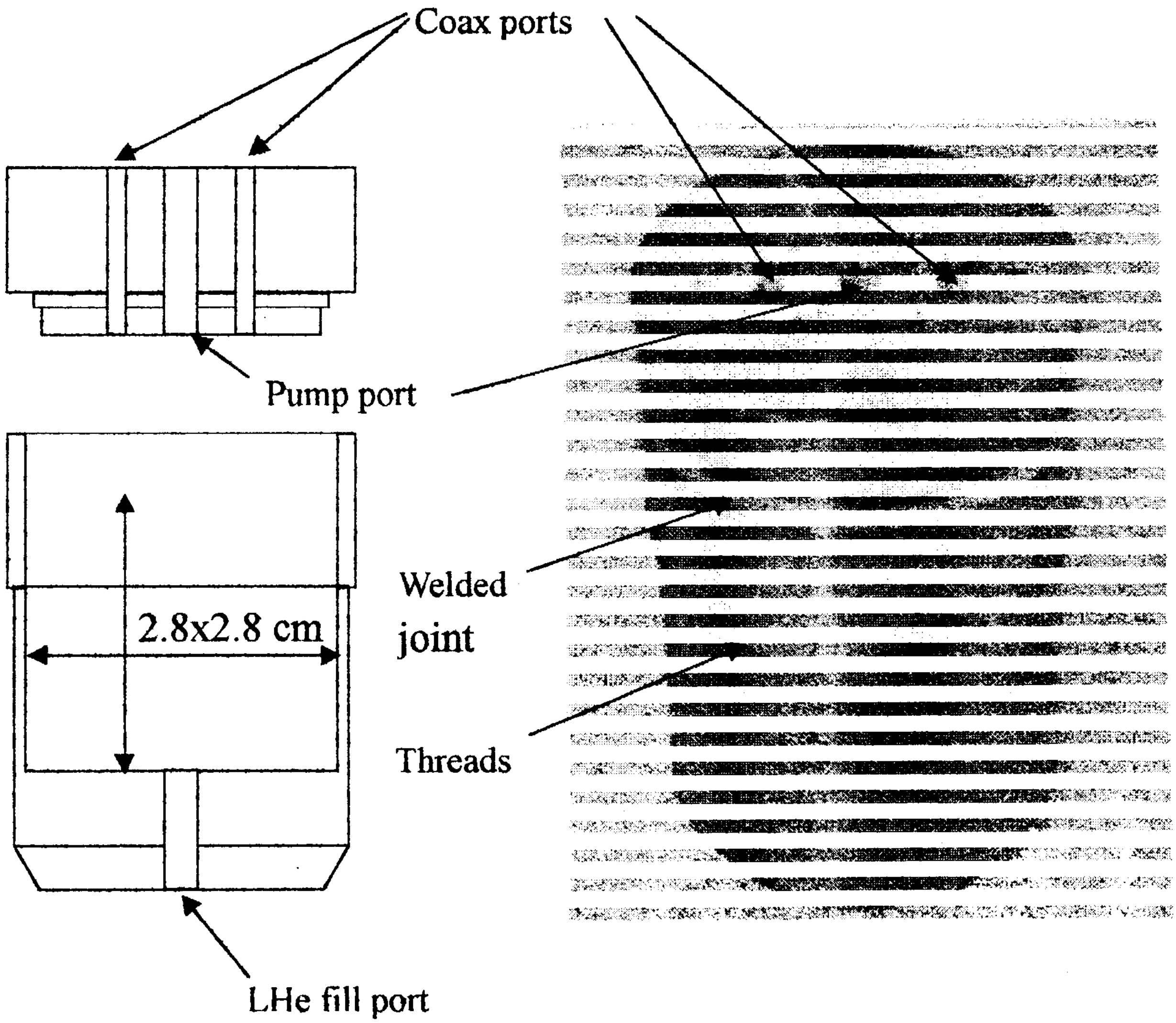
- $(1/f\ \partial f/\partial T) \sim -10^{-10}\ K^{-1}$ at 2 K. So we need to have temperature stability $\sim 10^{-7}$ K to obtain frequency stability $\sim 10^{-17}$.

- High-Resolution Thermometry uses a SQUID magnetometer with resolution of $\sim 10^{-10}$ K to obtain stability of $\sim 10^{-9}$ K.

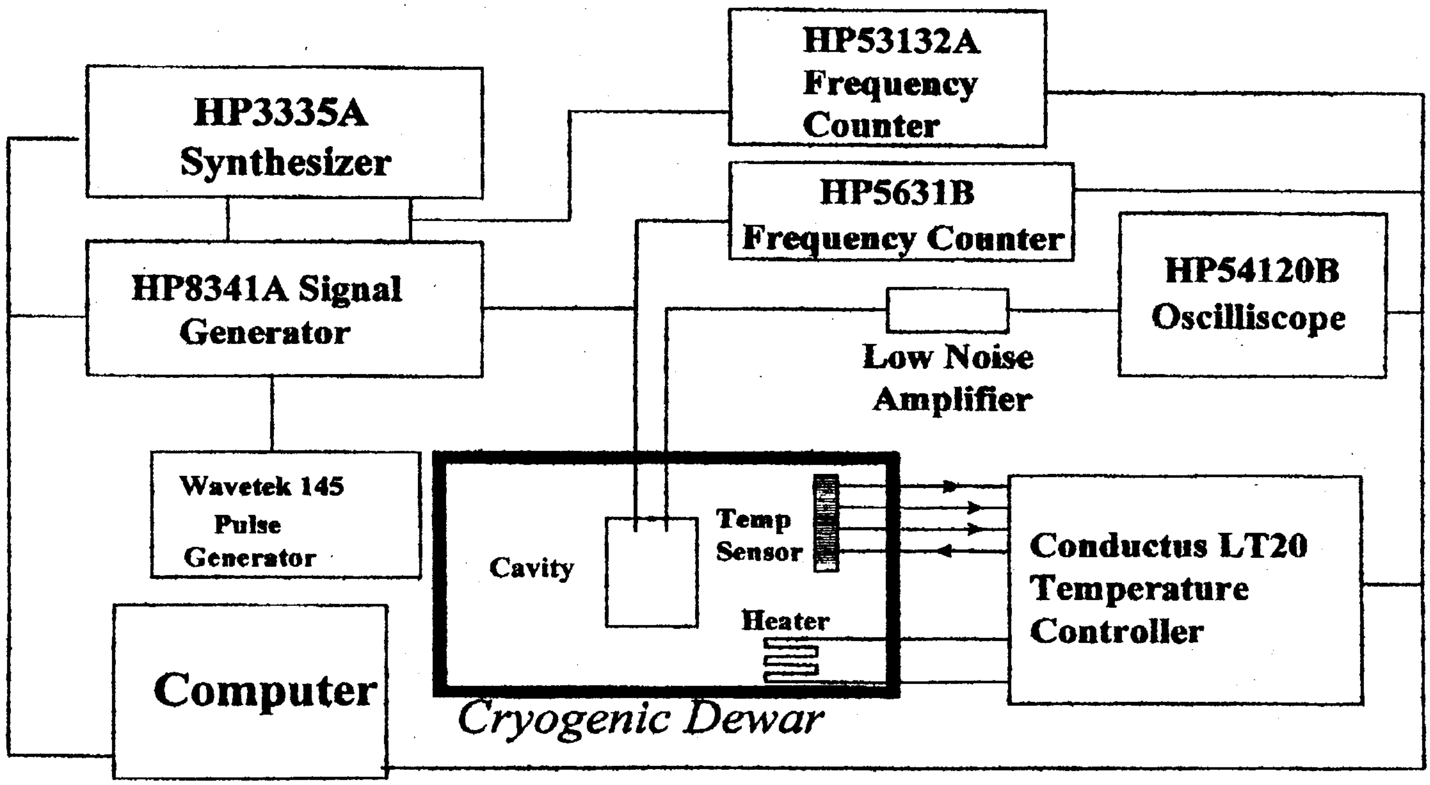


The Niobium Cavity

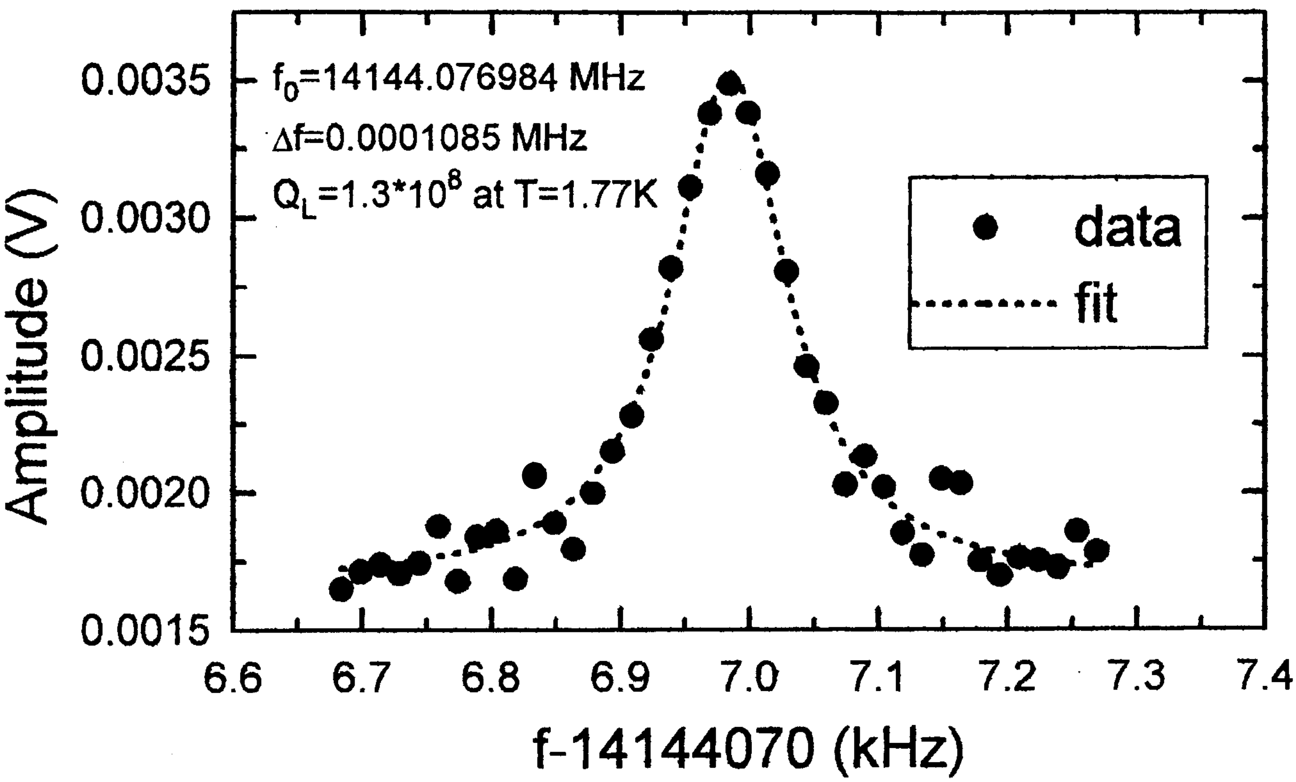
- Designed for TE_{011} mode at 14.12 GHz.
- A groove near the welded joint splits the degeneracy between TE and TM modes



Microwave Characterization System

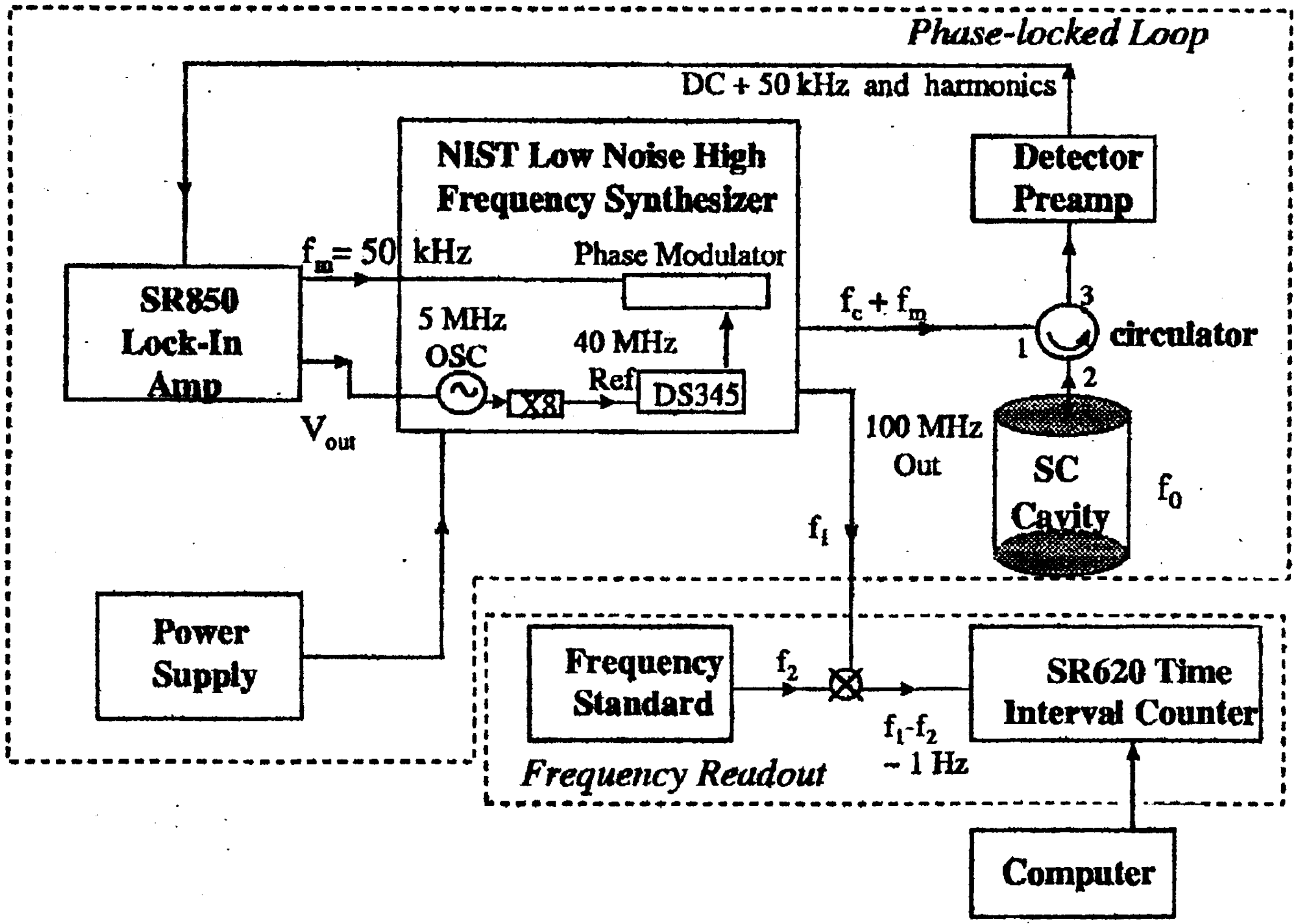


Characterization of Superconducting Cavity



RESULTS

- An anodized cavity gives a Q of 10^7 at 2K.
- A cavity etched in acid and annealed at 1400°C for 12 hours in ultra-high vacuum gives a Q of 10^8 at 1.77 K.
- Will attempt annealing at higher temperatures (near 1800°C) and for longer period of time.


Phase-locked Loop
DC + 50 kHz and harmonics
NIST Low Noise High Frequency Synthesizer
Detector Preamp
f_m= 50 kHz
Phase Modulator
SR850 Lock-In Amp
5 MHz OSC
40 MHz Ref
X8
DS345
$f_c + f_m$
3
1
2
circulator
V_{out}
100 MHz Out
SC Cavity
f_0
f_1
Power Supply
Frequency Standard
f_2
f_1-f_2
~ 1 Hz
SR620 Time Interval Counter
Frequency Readout
Computer

Quantifying Stability

1. In frequency domain, use the spectral density:

$$S_y(f) = \frac{S_\upsilon(f)}{\upsilon^2}$$

$S_\nu(f)$: spectral density of frequency fluctuations
$\nu(t)$: time-dependent instantaneous frequency
f : time-independent Fourier frequency

2. In time domain, use the Alan variance:

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle (\bar{y}_2 - \bar{y}_1)^2 \right\rangle$$

Estimator:

$$\sigma_y^2(\tau, m) = \frac{1}{2(m-1)} \sum_{i=1}^{m-1} (\bar{y}_{i+1} - \bar{y}_i)^2$$

$y_i = f(t_k + t)\text{-}f(t_k) /\tau$
τ : averaging time
m : number of samples